Comments on THEIA Long Baseline Physics

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Stony Brook University
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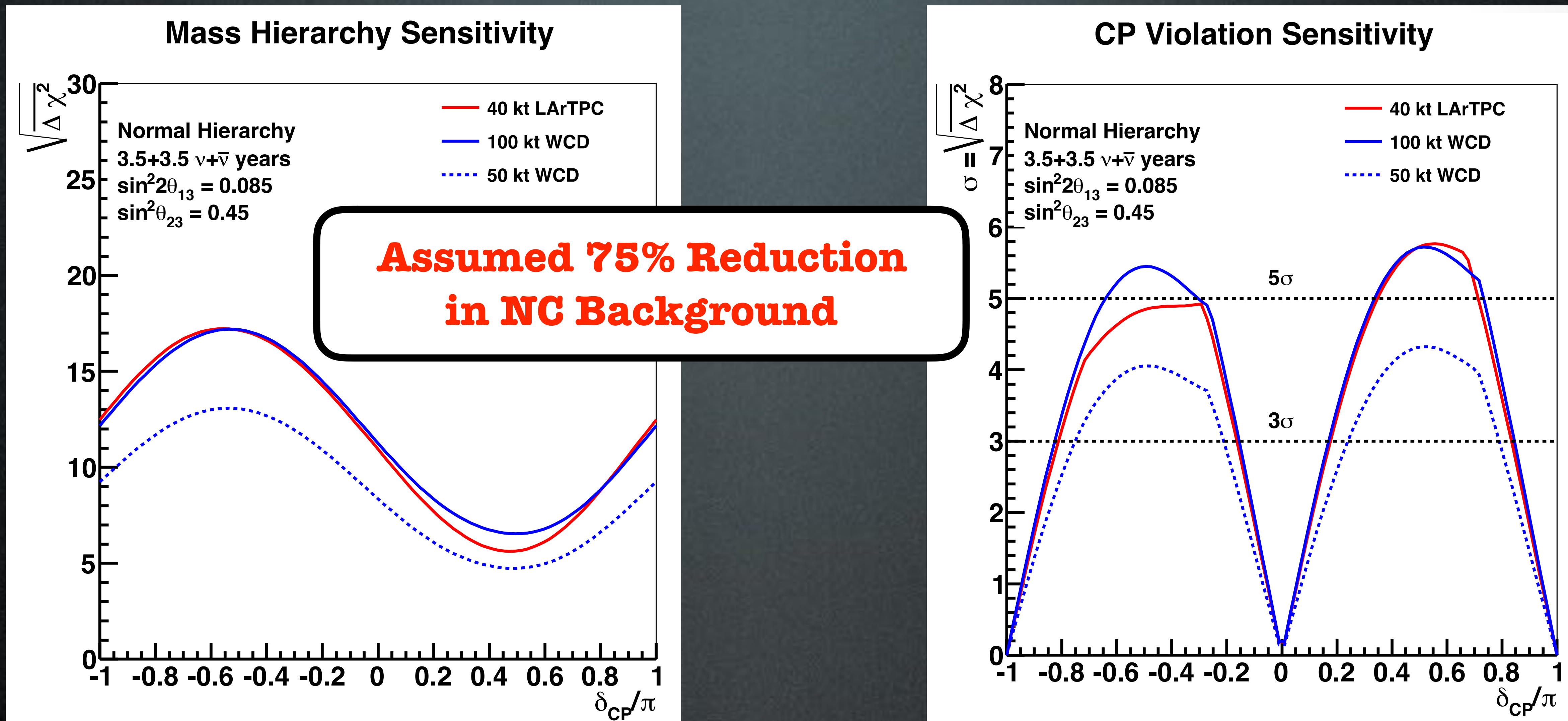
Overview

- Reconstruction in water Cherenkov detectors has advanced since the early LBNE sensitivity calculations
- We are beginning studies to determine how much more sensitive a WC detector in the DUNE beamline can be to CP violation
- Initial studies utilize atmospheric Monte Carlo in a Super-K sized detector
    - For future studies, a new simulation of a much larger detector is now available

“Elizabeth Plots”



- At the previous FroST meeting, E. Worcester showed that if the NC background is reduced by 75%, 40 kt of LAr produces the same sensitivity as 100 kt of water
- How realistic is this reduction, and what other improvements are possible?

fiTQun: An Event Reconstruction Algorithm for Super-K

- For each Super-K event we have, for every hit PMT
  - **A measured charge**
  - **A measured time**
- For a given event topology hypothesis, it is possible to produce a **change and time PDF for each PMT**
  - Based on the likelihood model used by MiniBooNE (NIM A608, 206 (2009))
- Framework can handle **any number of reconstructed tracks**
  - Same fit machinery used for all event topologies (e.g. e^- and π^0)
- Event hypotheses are distinguished by **comparing best-fit likelihoods**
  - electron / π^0
  - electron / muon / π^+ / K^+ / p / ...
  - 1-ring / 2-ring / 3-ring ...

The Likelihood Fit

$$L(\mathbf{x}) = \prod_{\text{unhit}} P(i\text{unhit}; \mathbf{x}) \prod_{\text{hit}} P(i\text{hit}; \mathbf{x}) f_q(q_i; \mathbf{x}) f_t(t_i; \mathbf{x})$$

- A single track can be specified by a **particle type**, and **7 kinematic variables** (represented above as the vector **x**):
  - A vertex position **(X, Y, Z, T)**
  - A track momentum **(p)**
  - A track direction **(θ, φ)**
- For a given **x**, a charge and time PDF is [hidden behind the callout box] every PMT
- The **charge PDF** is factorized into:
  - Number of photons reaching the PMT
    - **Predicted charge (μ)**
  - PMT & electronics response
- All 7 track parameters **fit simultaneously**

Calculating μ is the main challenge

Time PDF

Charge PDF

PMT Charge Response:

Property of the electronics and PMT properties

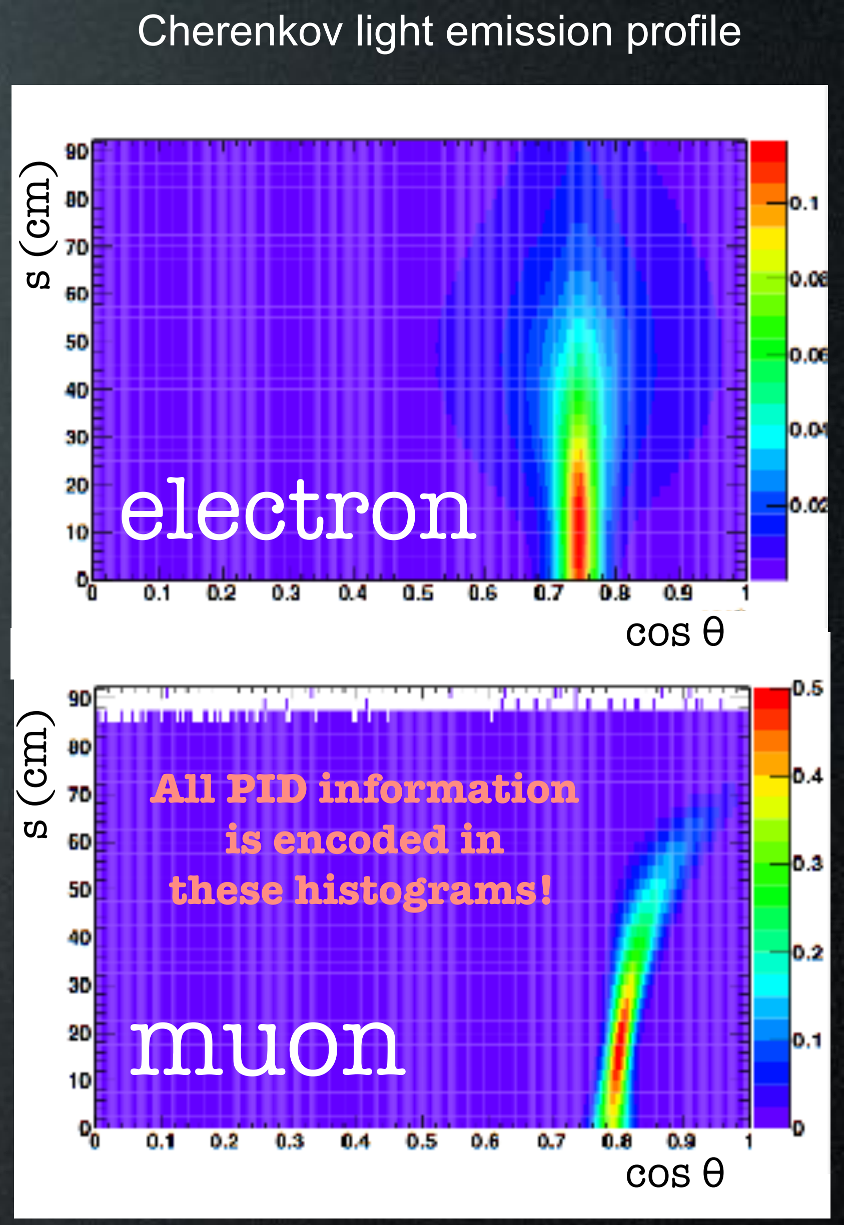
Predicted Charge (μ):

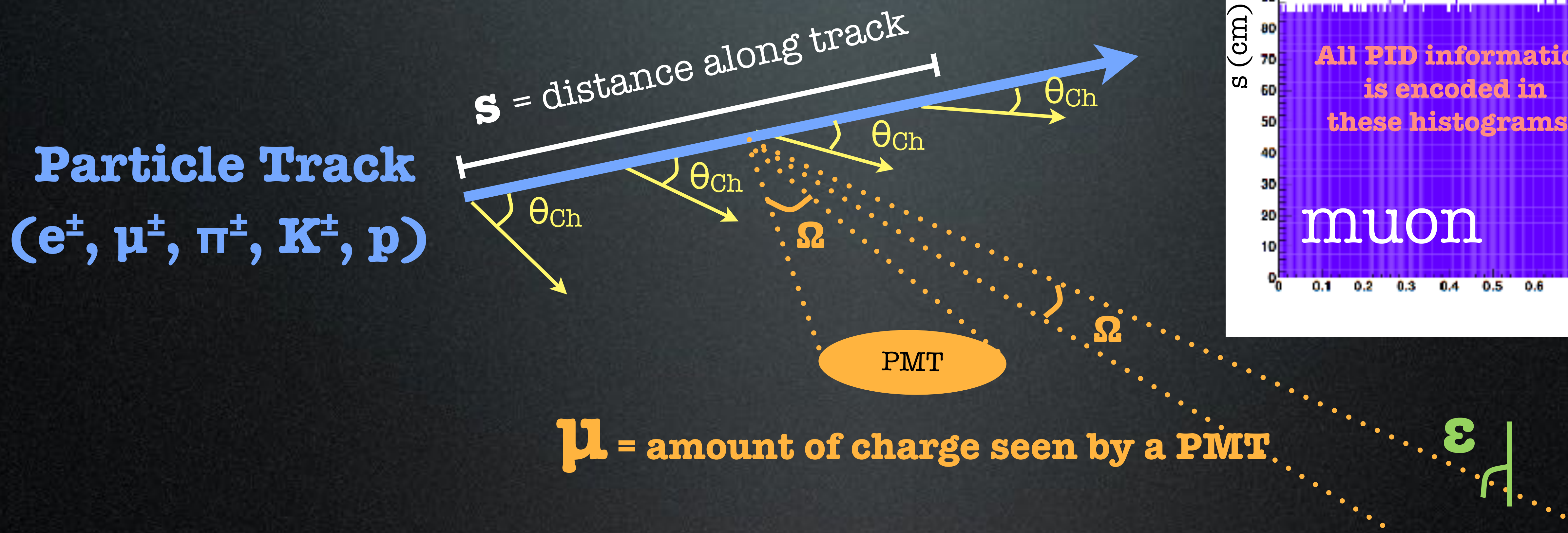
- Number of photons that reach the PMT
- Depends on detector properties (scat, abs, etc.)

Predicted Charge (μ)

$$\mu = \Phi(p)\int ds\, g(s, cos\theta)\Omega(R)T(R)\epsilon(\eta)$$

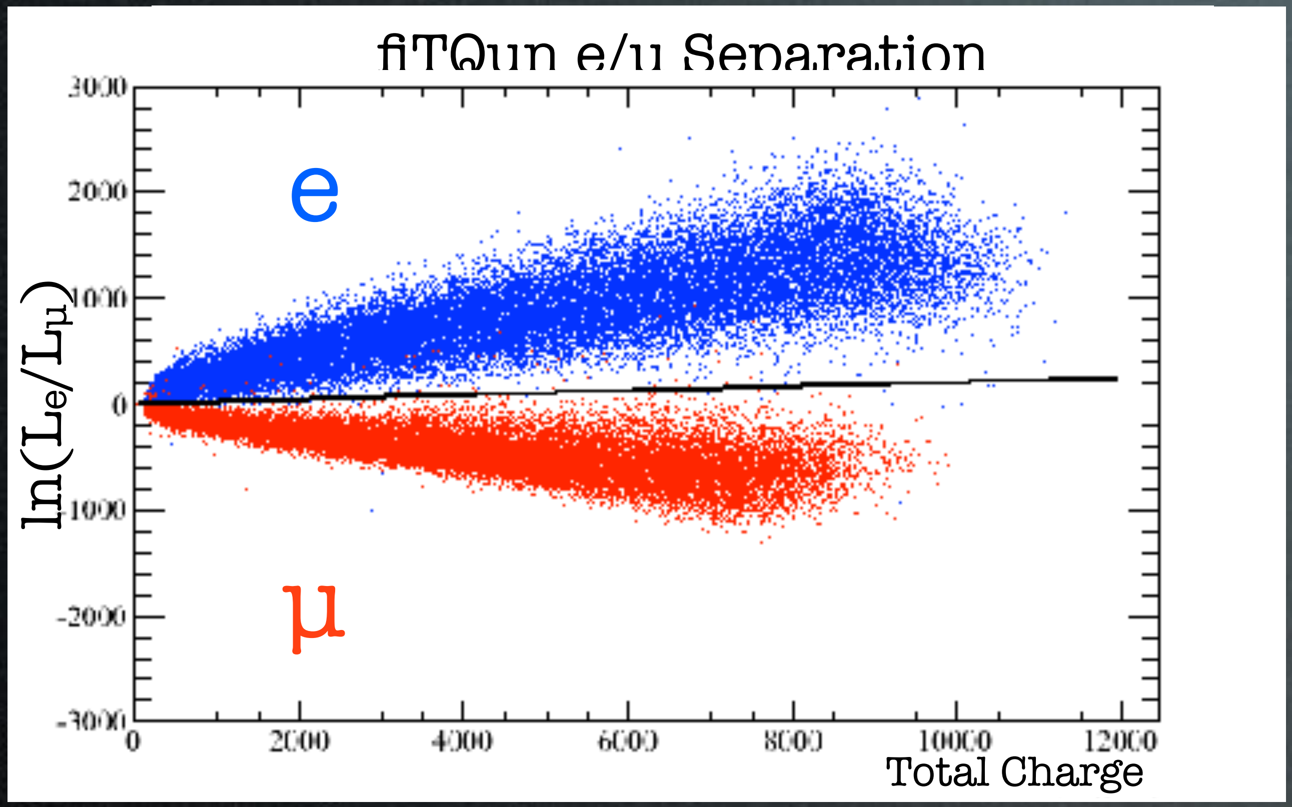
- Light Yield (normalization)
- Integral over track length
- PMT solid angle
- Water attenuation
- PMT angular response



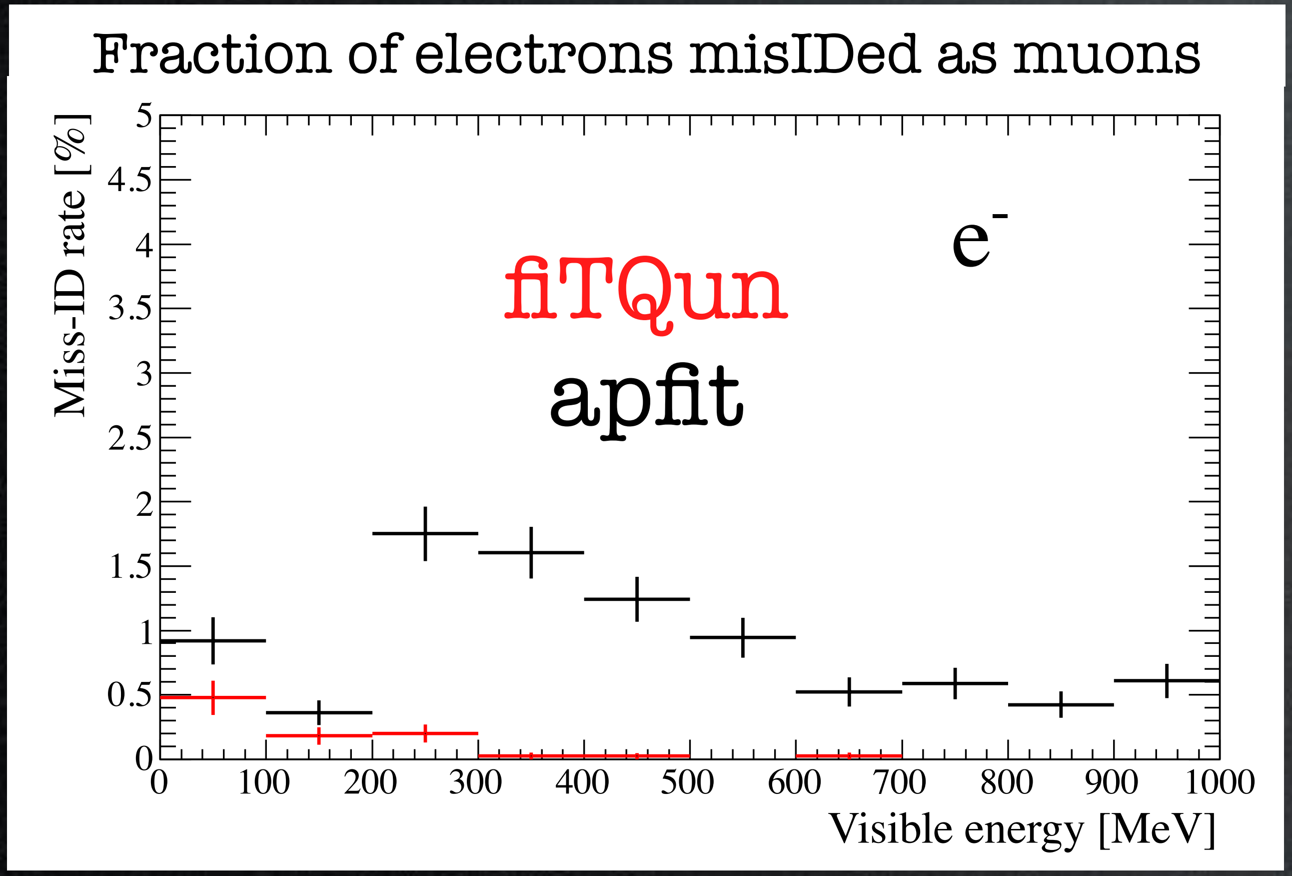


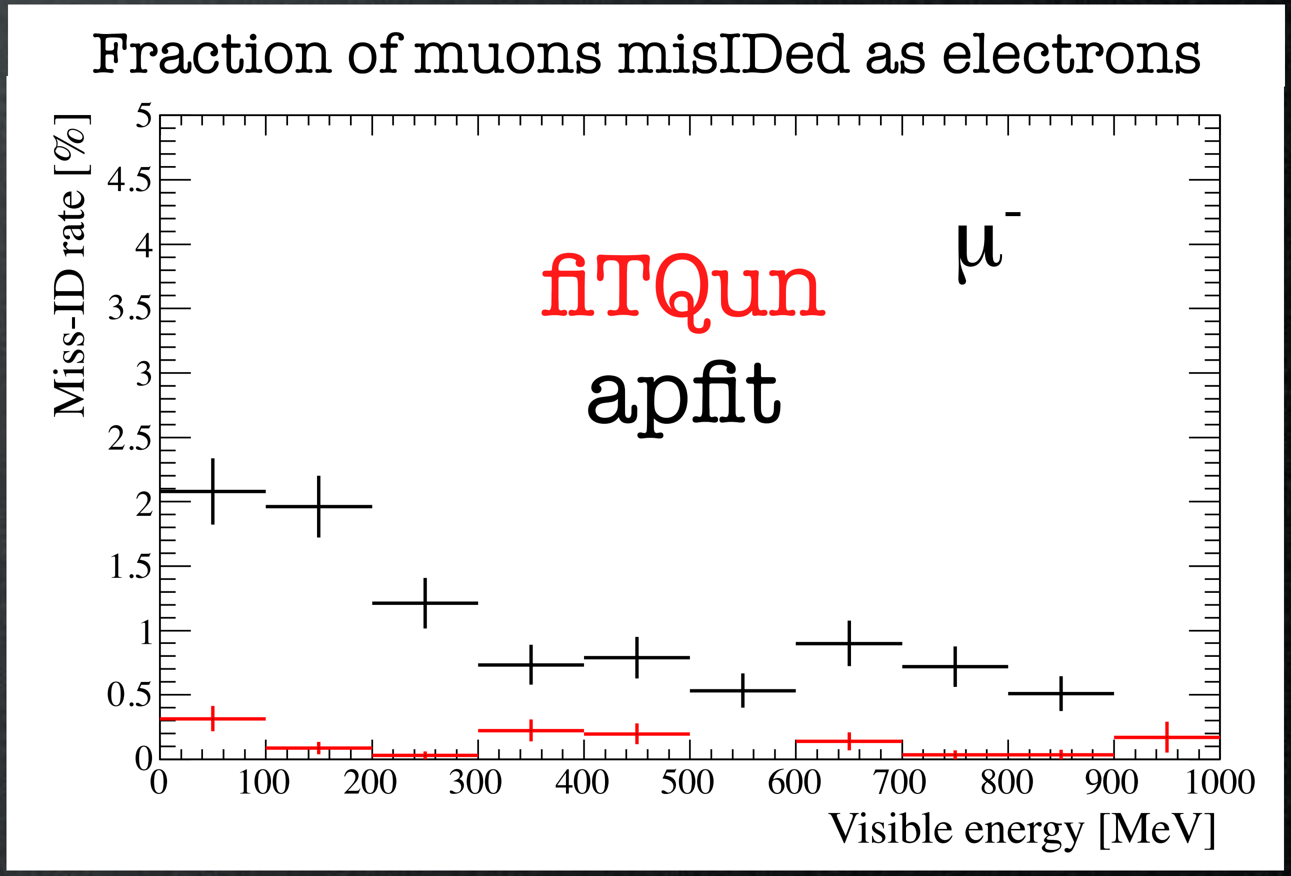
- For multi-particle states, predicted charges are summed
- Scattered and reflected light is treated separately (and more crudely: tabulation)

Single Track Particle ID



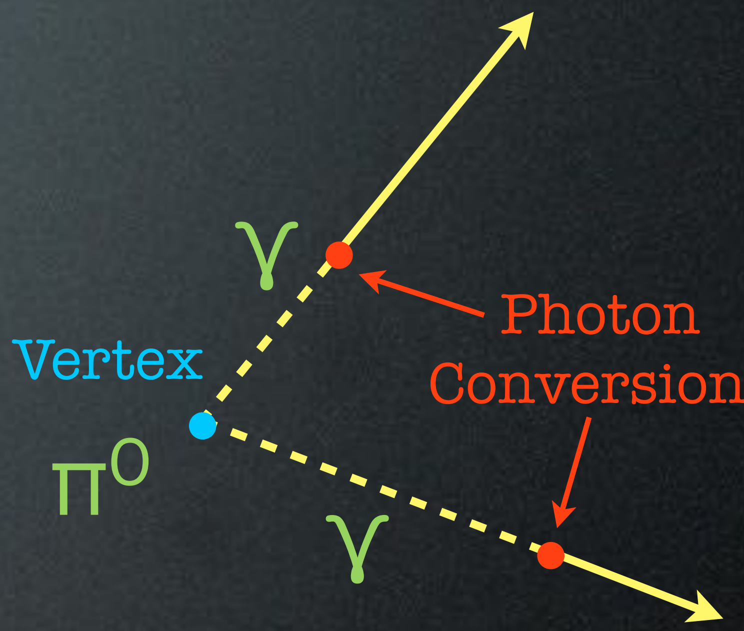
- Simple line cut can be used to separate muons and electrons
- Significantly improved particle ID

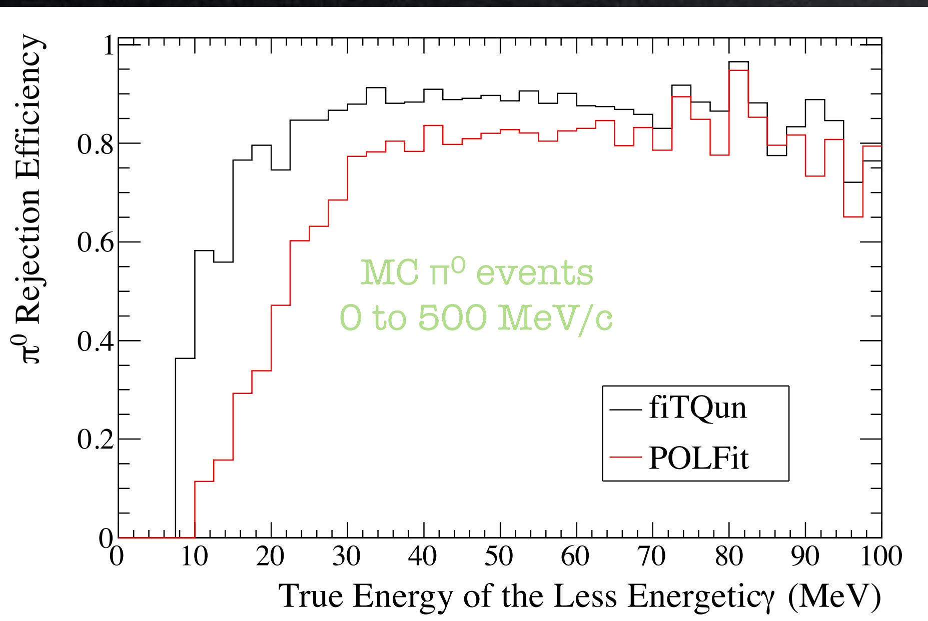


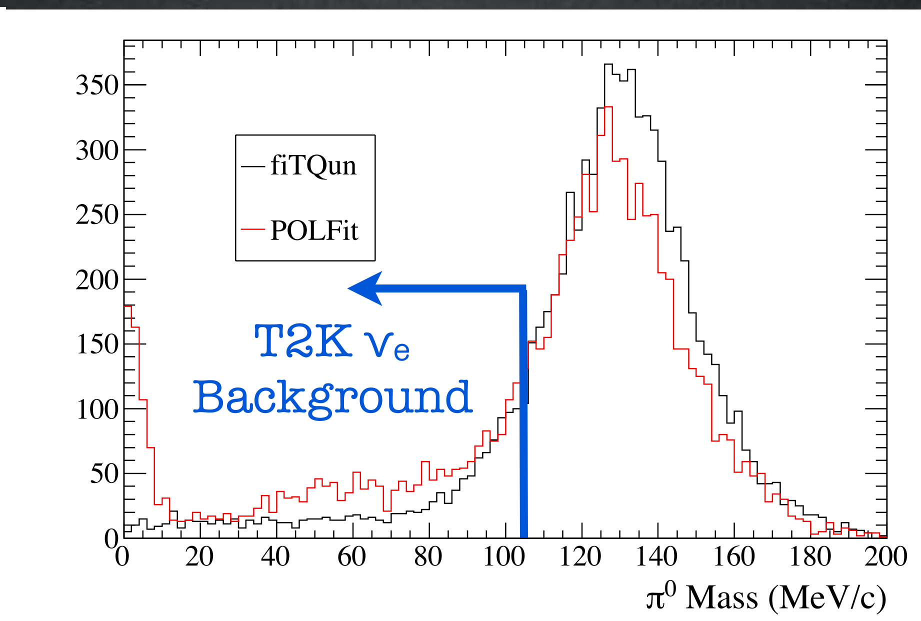


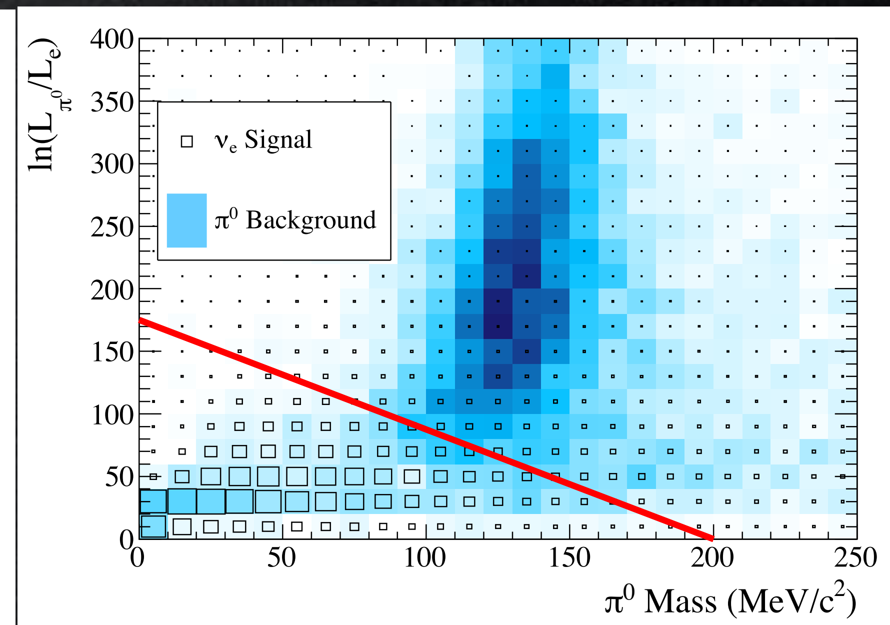
FiTQun π^0 Fitter

- Assumes two electron hypothesis rings produced at a common vertex
- **12 parameters** (single track fit had 7)
  - Vertex (X, Y, Z, T)
  - Directions (θ_1, φ_1, θ_2, φ_2)
  - Momenta (p_1, p_2)
  - Conversion lengths (c_1, c_2)
- Large improvement in finding low energy 2nd ring
  - ~70% reduction in π^0 background relative to POLFit (not used in LBNE studies)





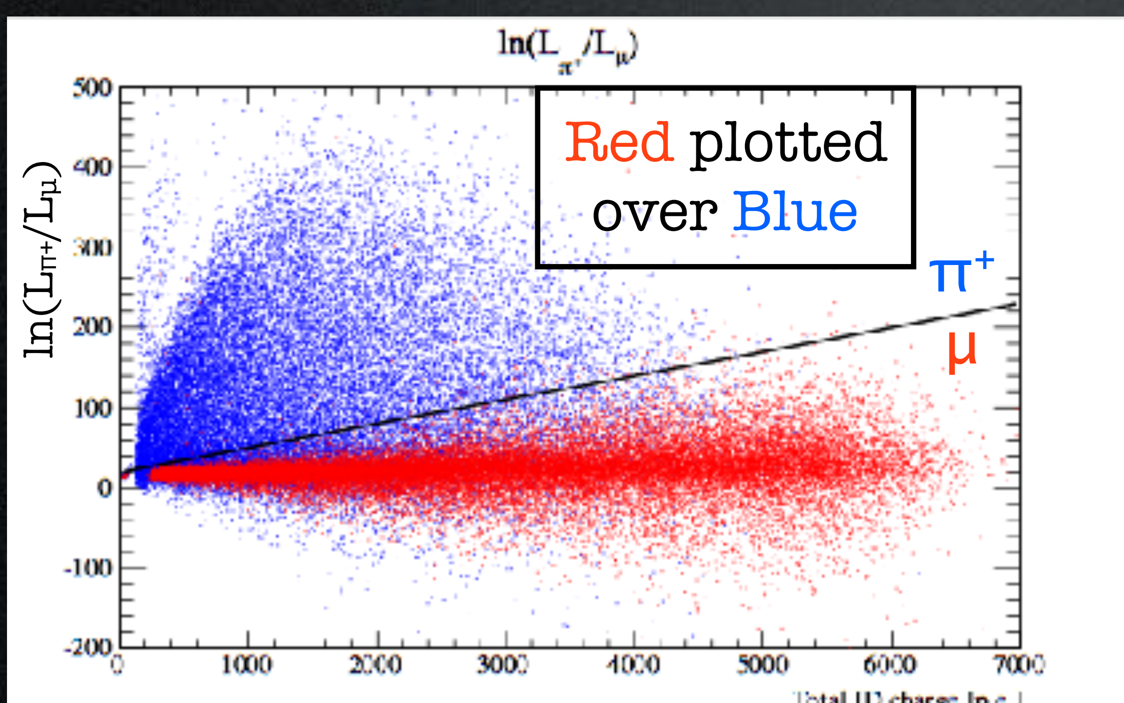


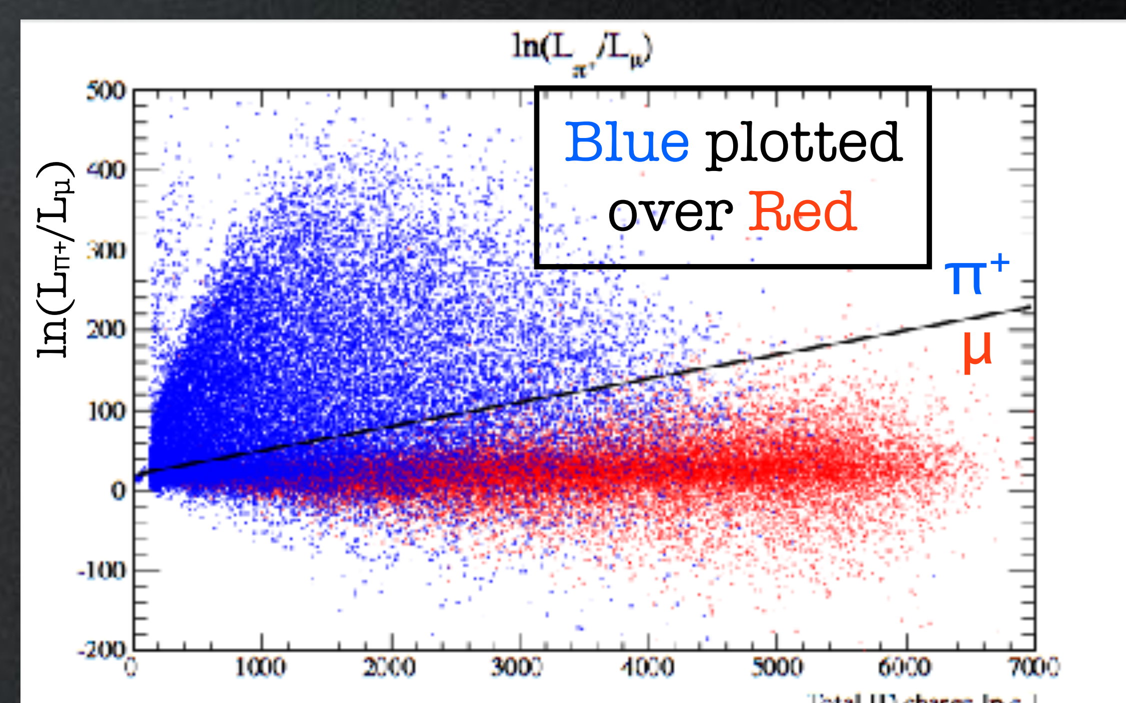


Other fiTQun Tools: π^+ Fitter

- Pions and muons have **very similar Cherenkov profiles**
  - Main difference is the **hadronic interactions** of pions
- Ring pattern observed is a **"kinked" pion trajectory** (thin ring with the center portion missing)
- New ability to separate charge pions from muons

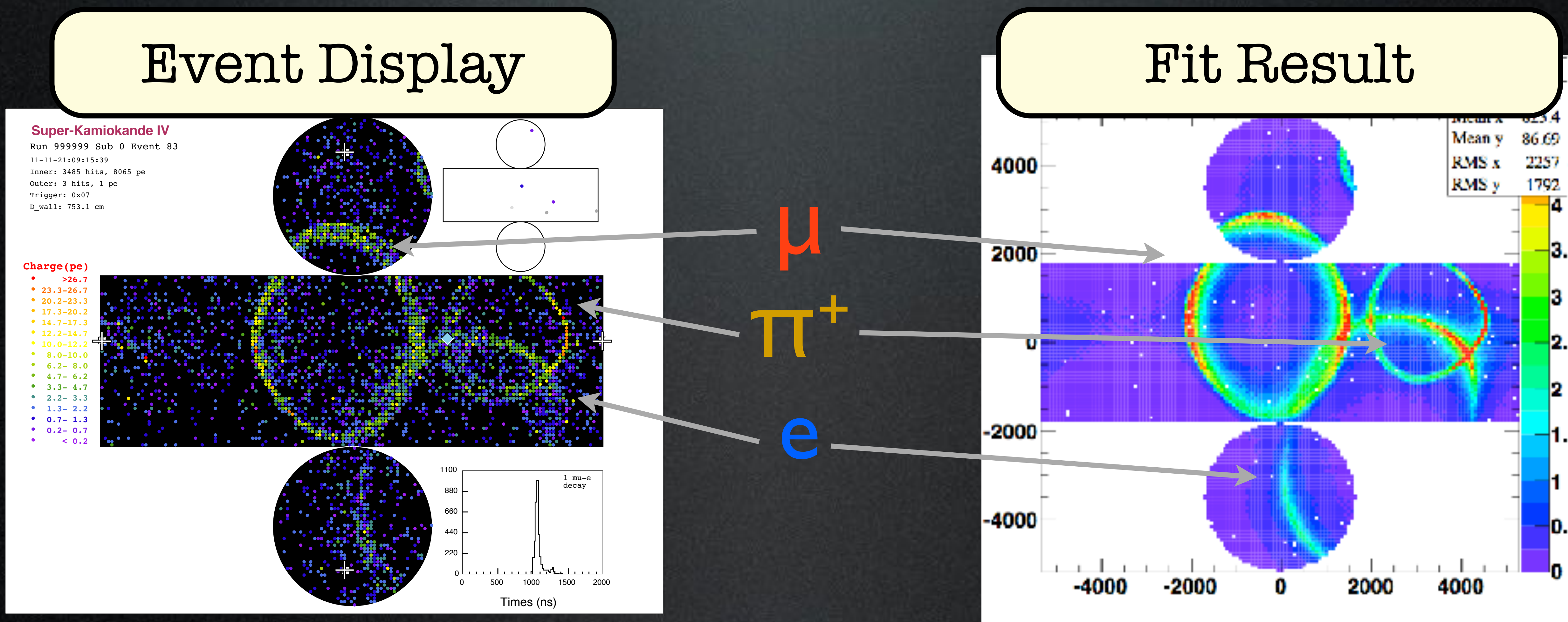
μ & π^+ particle gun





Multi-ring Fitter

- **Fit up to 6 rings** using e & π^+ hypotheses28 fits in total (every possible e/π^+ combination)
- μ hypothesis is a subset of the π^+ hypothesis (no "thin" ring from hadronic interactions)
- Can now separate pion, muon, and electron rings



Original LBNE ν_e Studies

Pre-Cut Efficiencies

$$\varepsilon(category, E_{bin}) = \frac{N_{precut}}{N_{neutrino}}$$

N_{precut} requires:
- reconstructed vertex in FV
- fully-contained (no OD activity)
- Evis > 100 MeV
- 1-ring
- e-like
- 0 mu-e decay

$N_{neutrino}$ requires:
- true vertex in FV

category:

ν_e QE
ν_e NQE
ν_μ CC
NC

$\otimes$

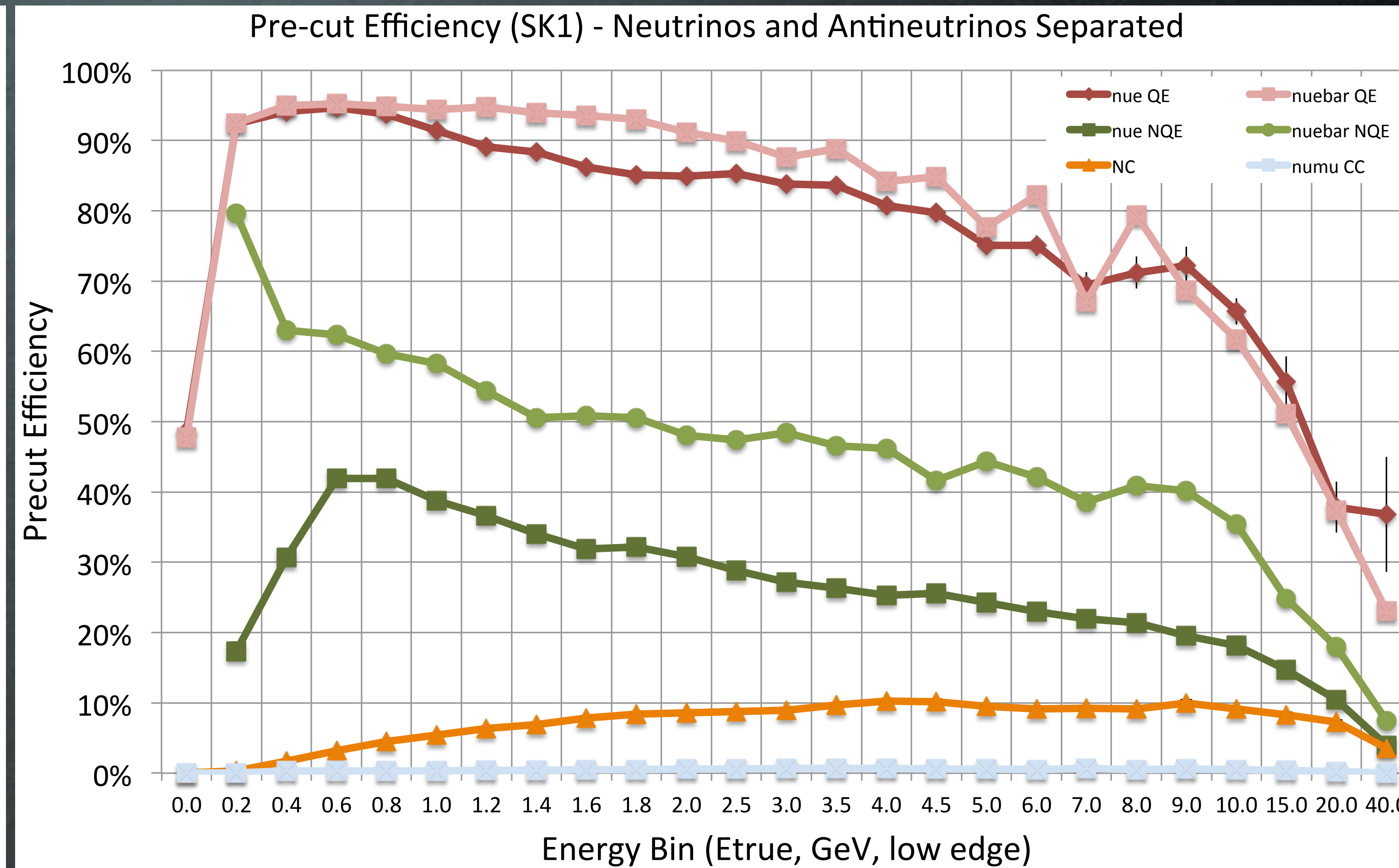
all
neutrino only
antineutrino only

$\otimes$

SK1 (40% PMT coverage)
SK2 (20% PMT coverage)

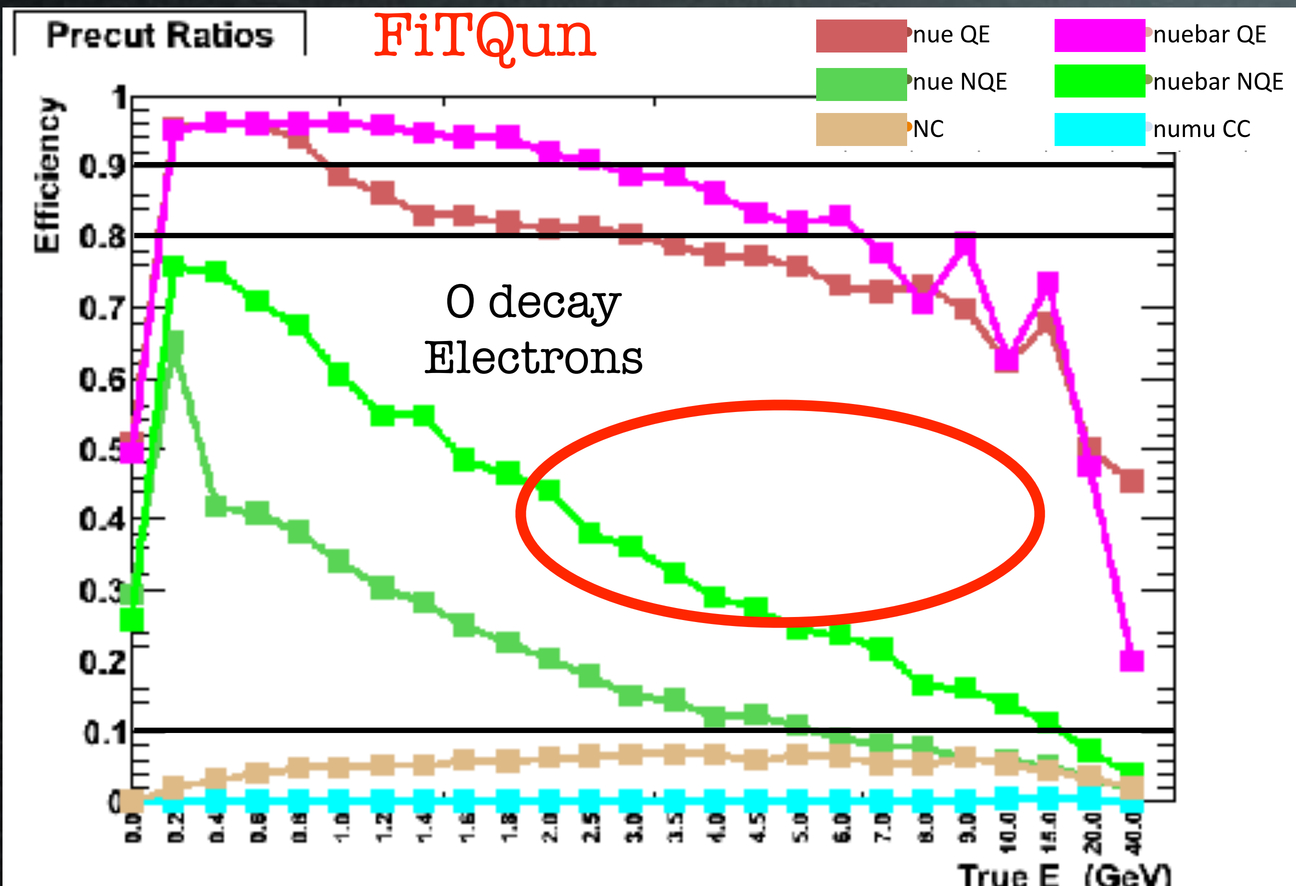
Ed Kearns
Boston University
November 4, 2011

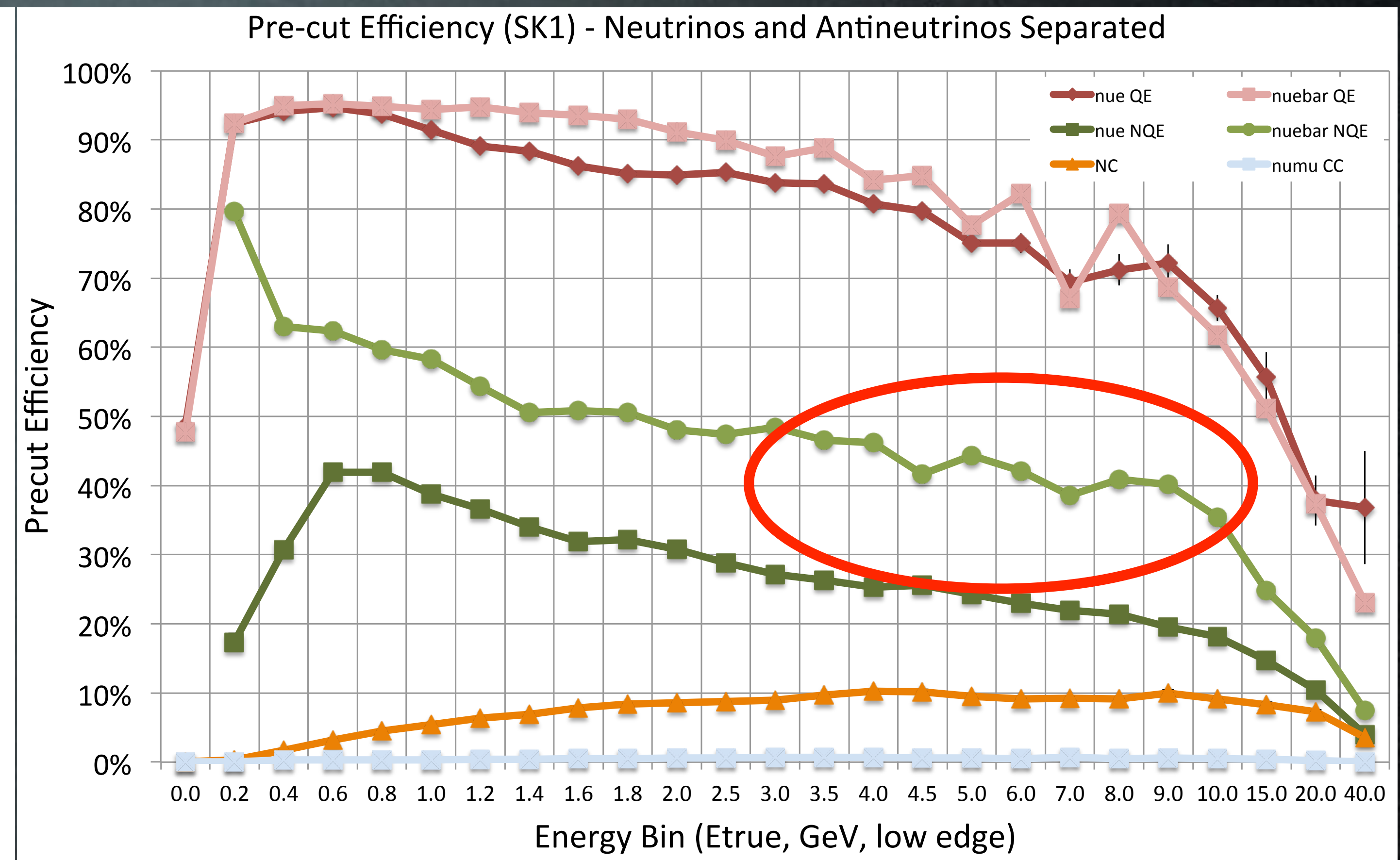
So technically, $\varepsilon > 1$ is possible if events migrate into fiducial volume



- Original studies based on SK1/SK2 MC
- Standard ν_e “pre-cut” selection applied
  - 1-ring, e-like, with **ZERO** decay electrons
- “Post-cut” is an additional cut designed to remove pi0 events

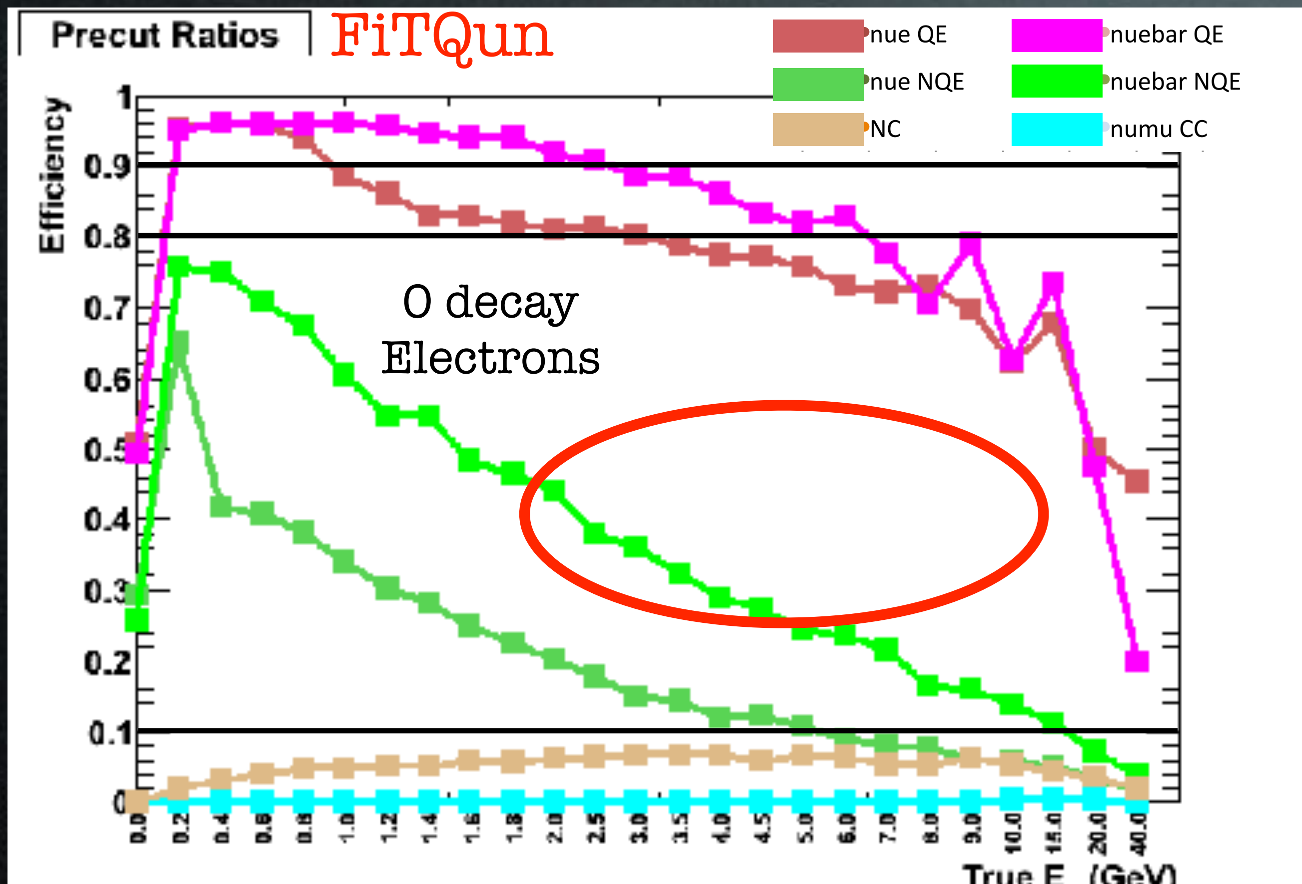
FiTQun “Pre-cuts”

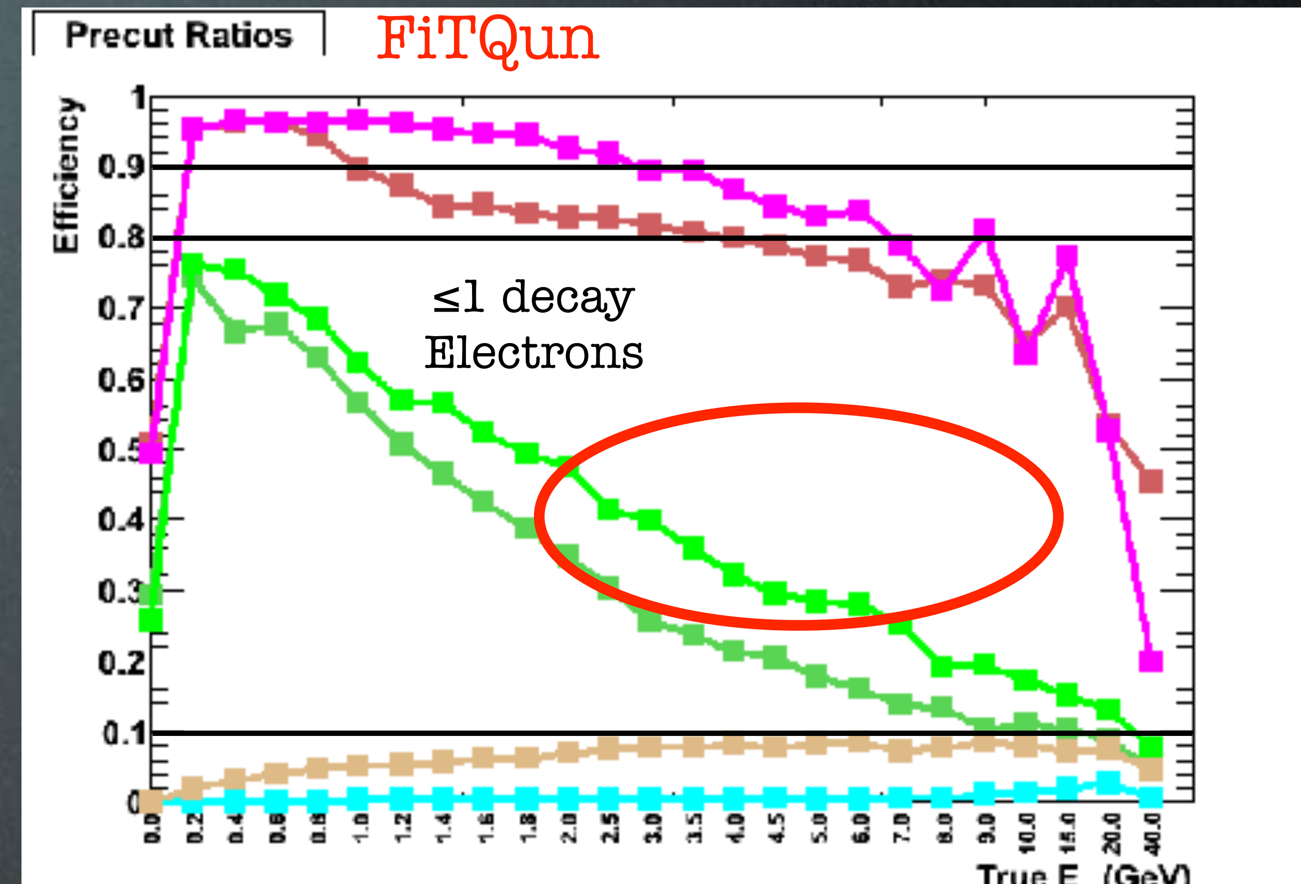




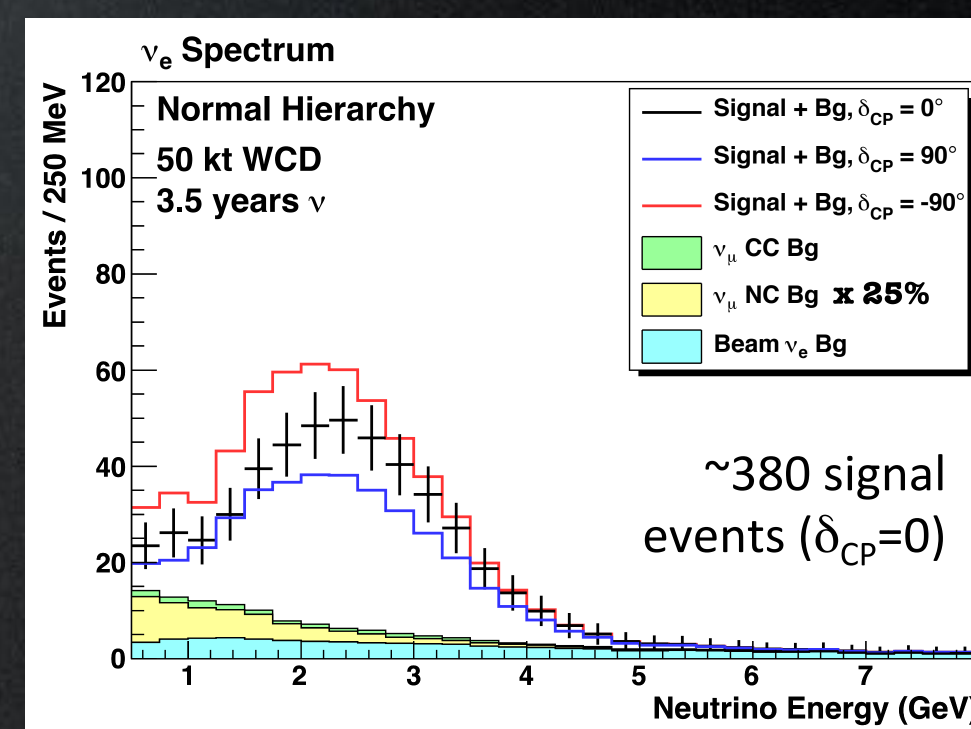
- Similar efficiencies for CCQE events
- Noticeably smaller efficiency for CCnQE
  - Improved ring counting reduces multi-ring samples (more on this later)
- NC events already significantly lower

FiTQun “Pre-cuts”

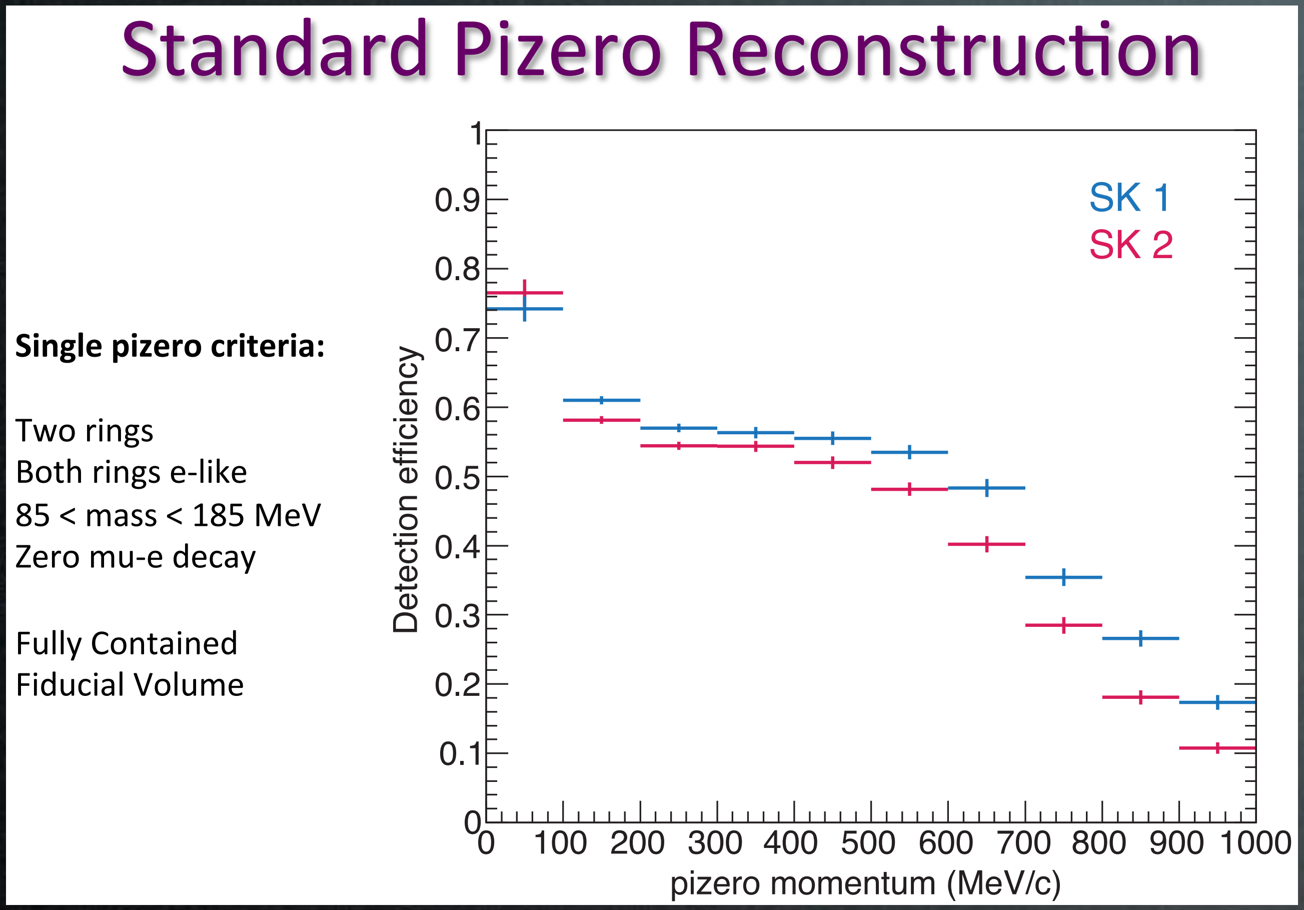


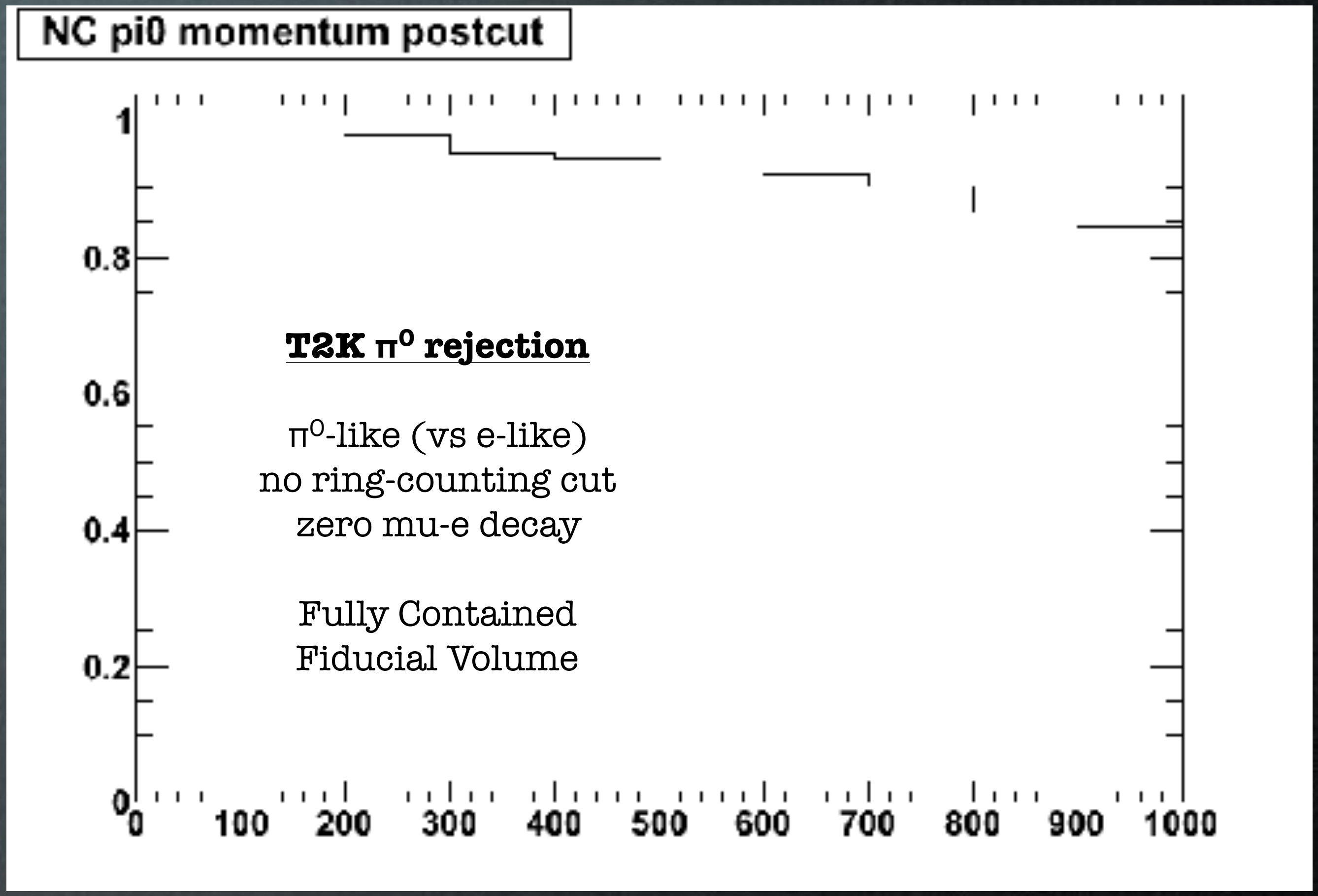


- By relaxing the zero decay electron requirement, can enhance the “1-ring” $CC\pi^+$ events
  - Very large gain in ν_e CCnQE (nearly double at the 1st oscillation maximum)
  - This sample resulted in a 13% statistics increase in the most recent T2K ν_e analysis



π^0 Rejection



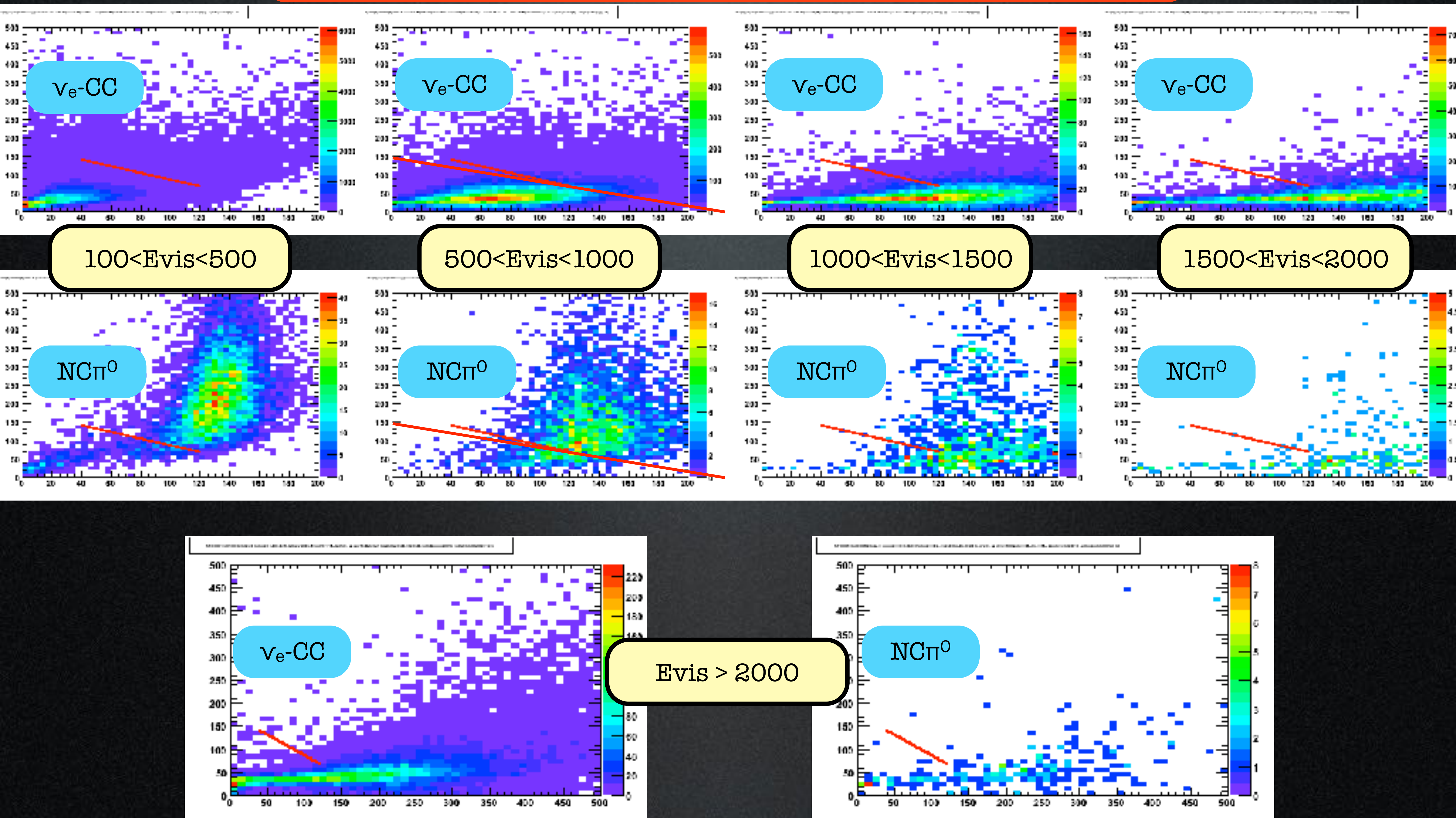


- Naively applying the T2K FiTQun pi0 rejection cut seems very promising
- However, this is very misleading
- Current cut is optimized for T2K (i.e. lower) energy flux
    - Large loss of efficiency at higher energies

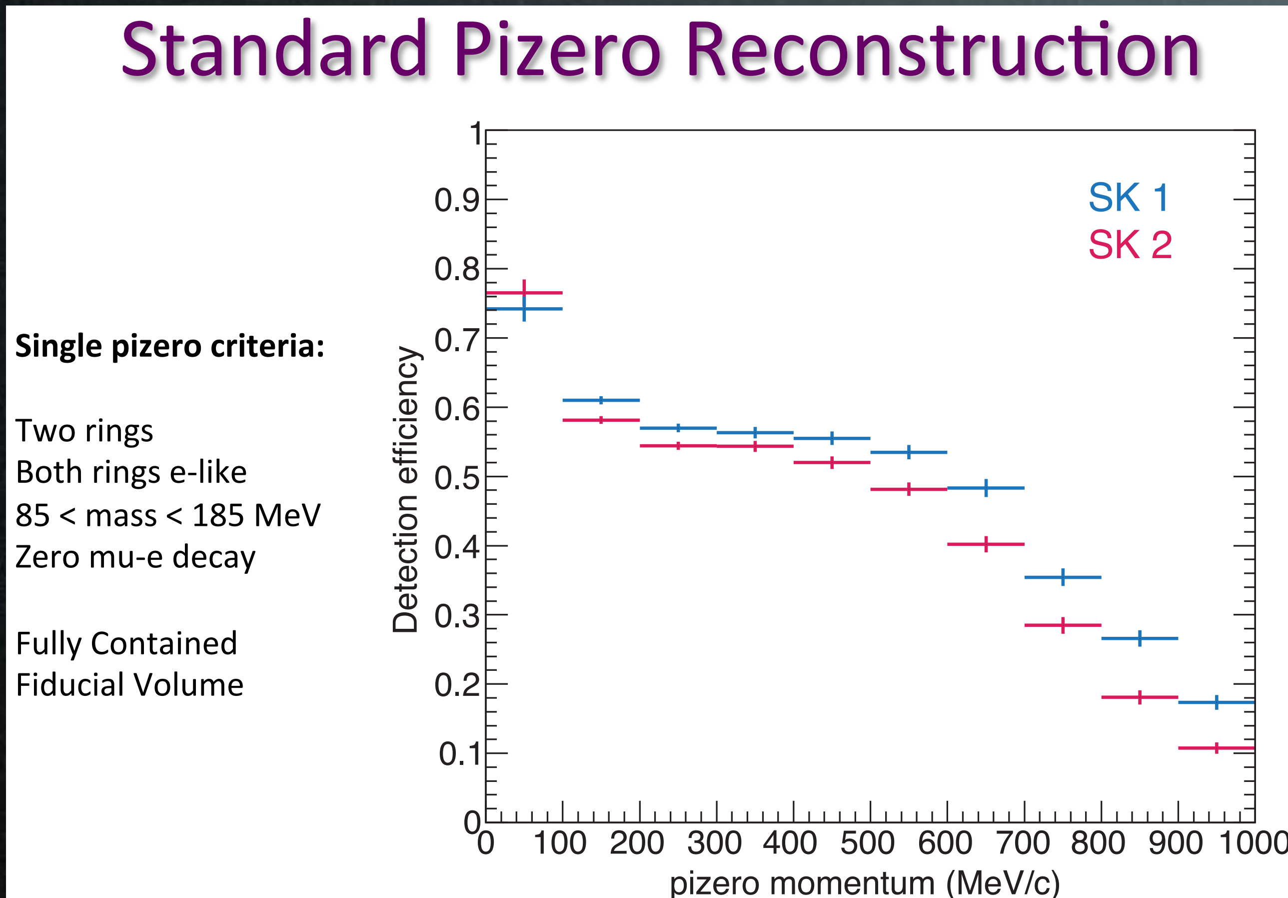
π^0 Cut at High E_{vis}

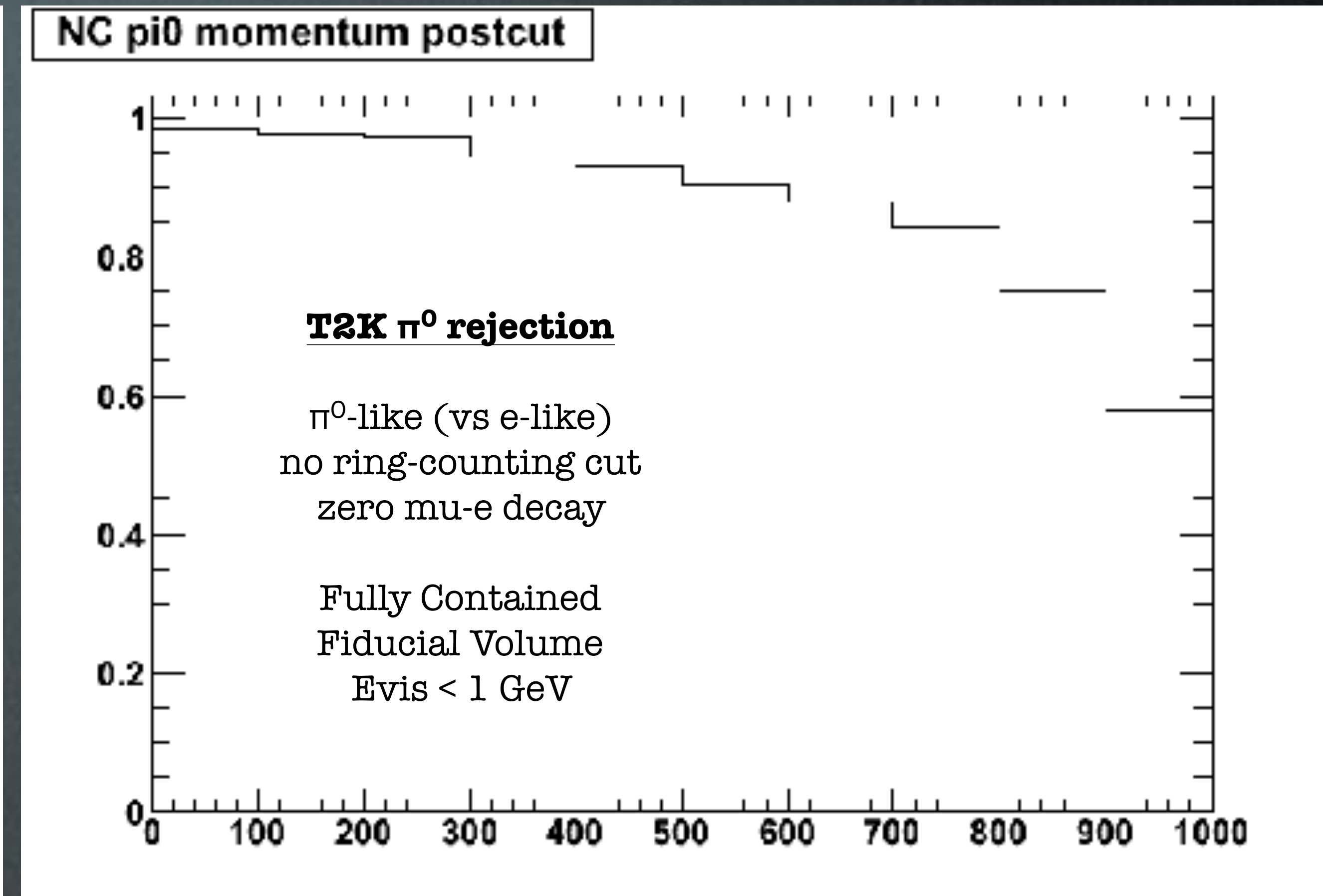
- The current π^0 cut is not optimized for high energy events

$\ln(L_{\pi0}/L_e)$ vs $M_{\pi0}$ for the ATM MC Sample

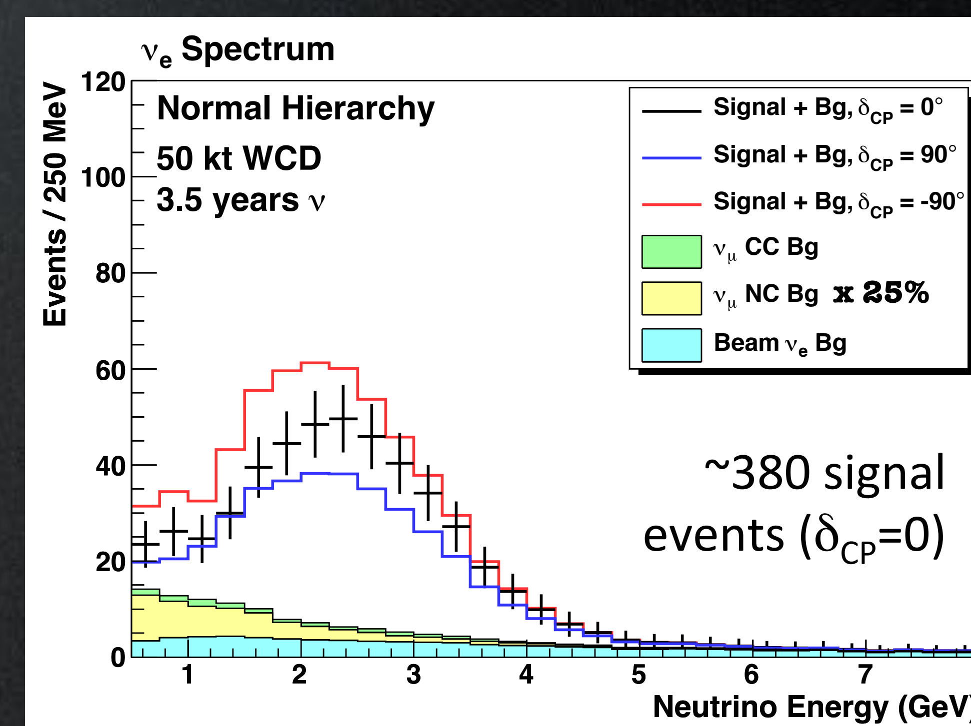


π^0 Rejection II



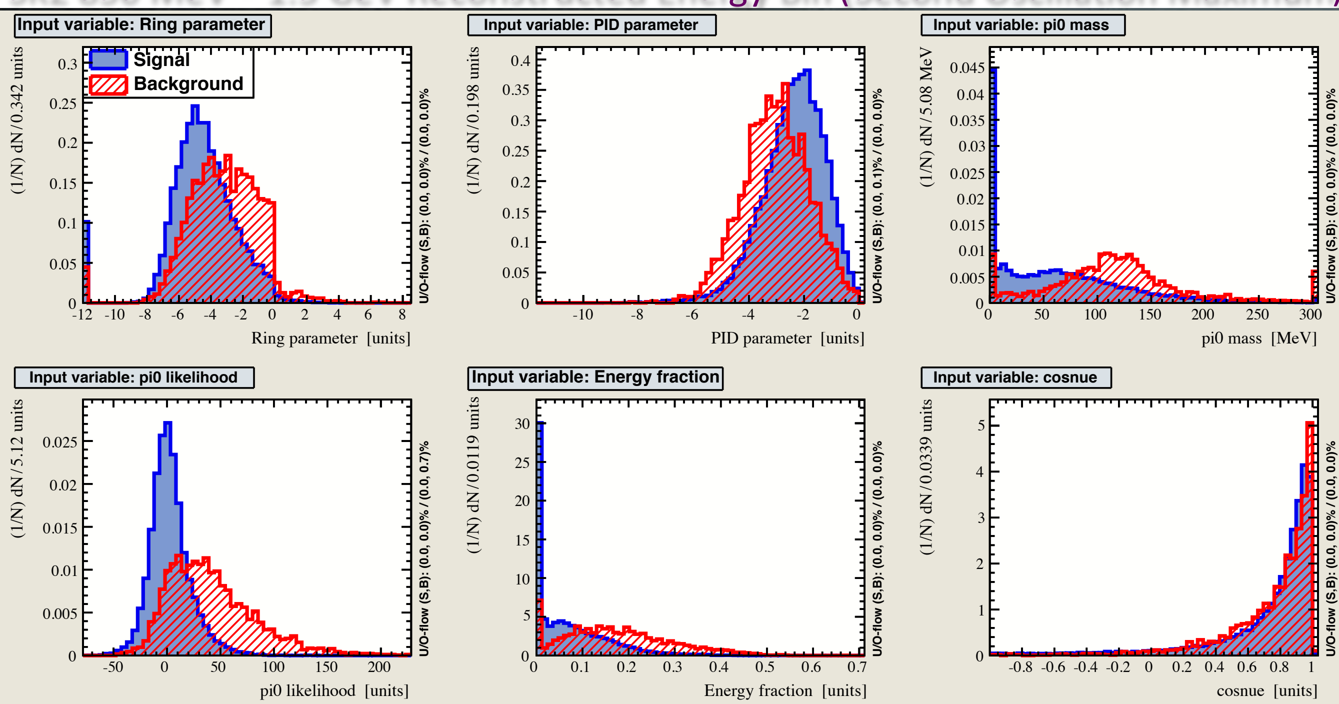


- What if we only apply the existing cut below Evis of 1 GeV?
  - Still can achieve fairly high π^0 rejection (up to 1 GeV/c π^0 momentum)
- Which energy regions are the most important? Need a full sensitivity study
- Ultimately, a cut should be designed that varies with Evis

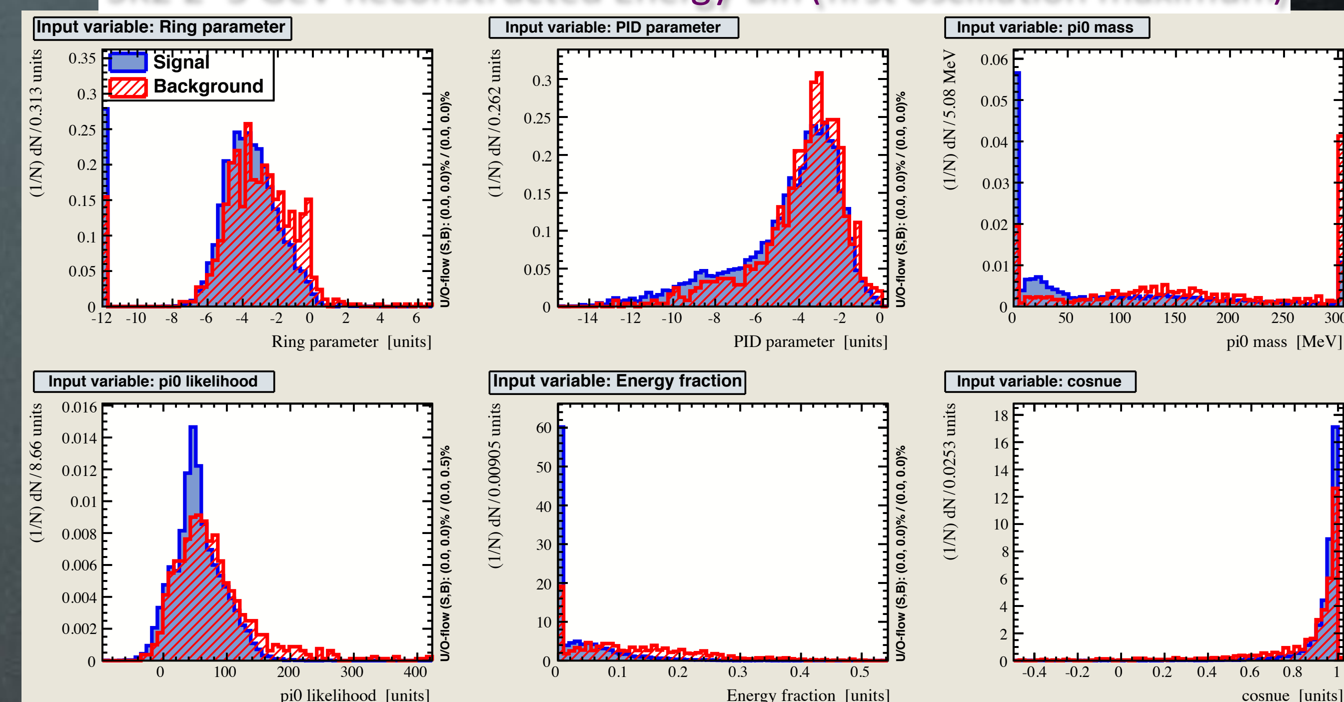


Final LBNE π^0 Rejection

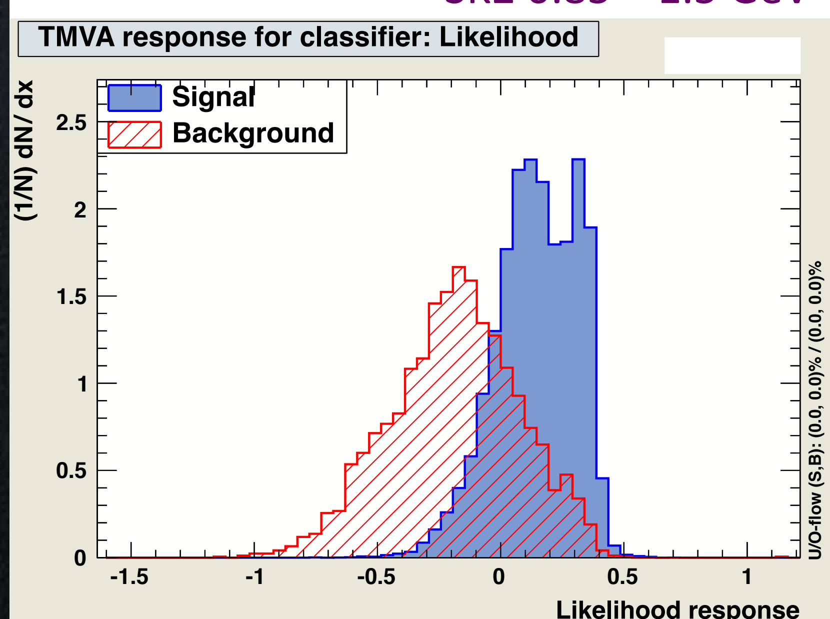
SK2 850 MeV – 1.5 GeV Reconstructed Energy Bin (Second Oscillation Maximum)



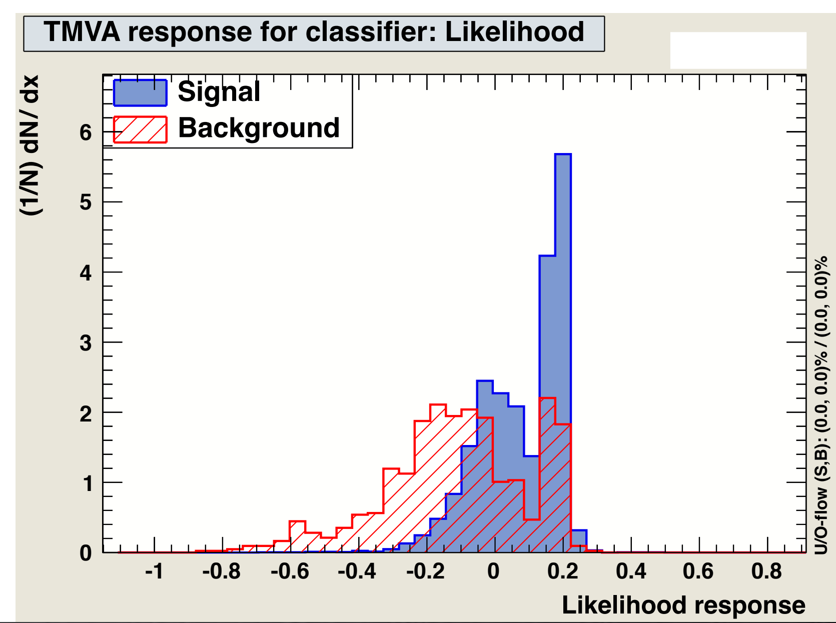
SK2 2–3 GeV Reconstructed Energy Bin (first oscillation maximum)



SK2 0.85 – 1.5 GeV

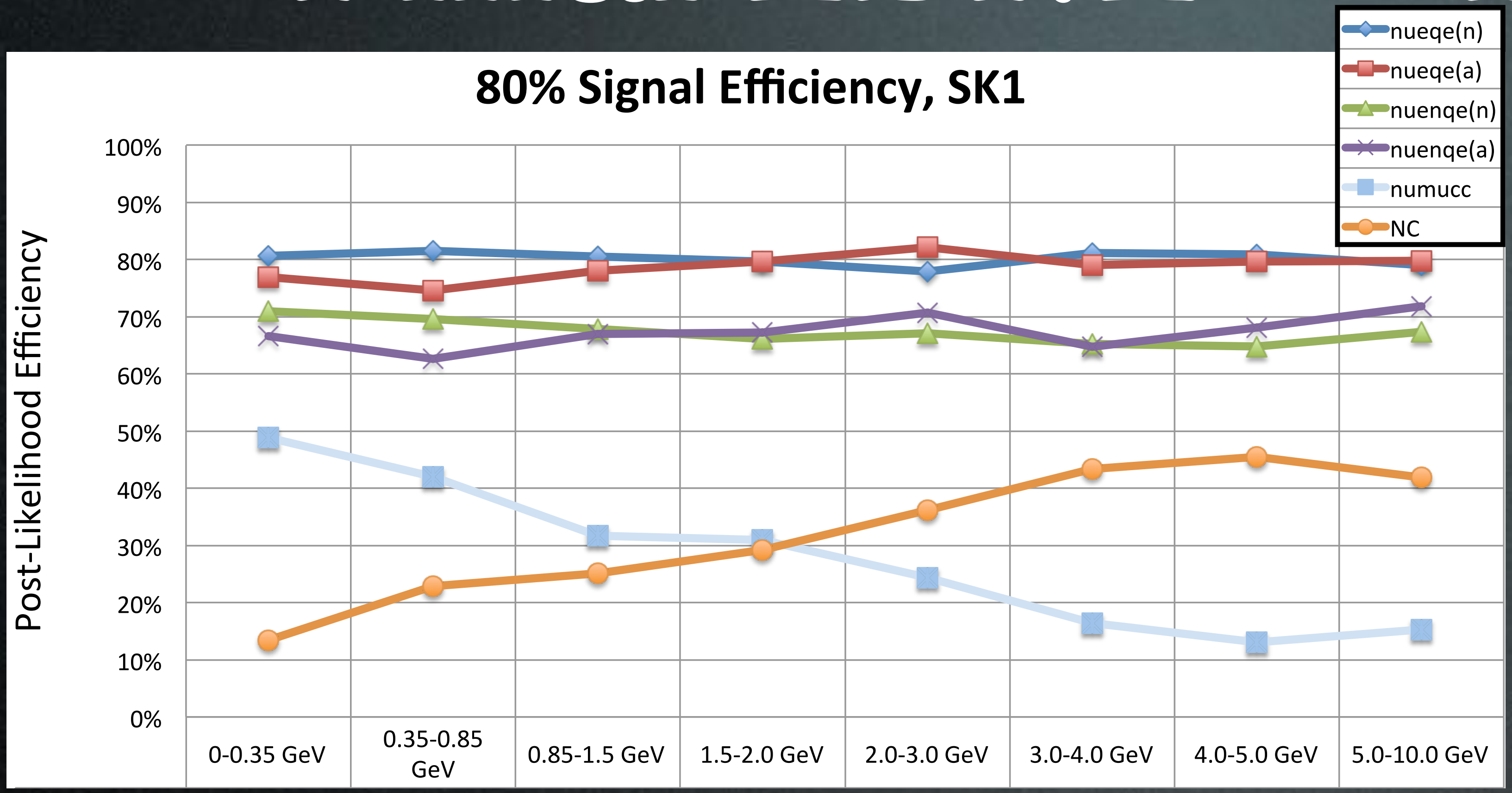


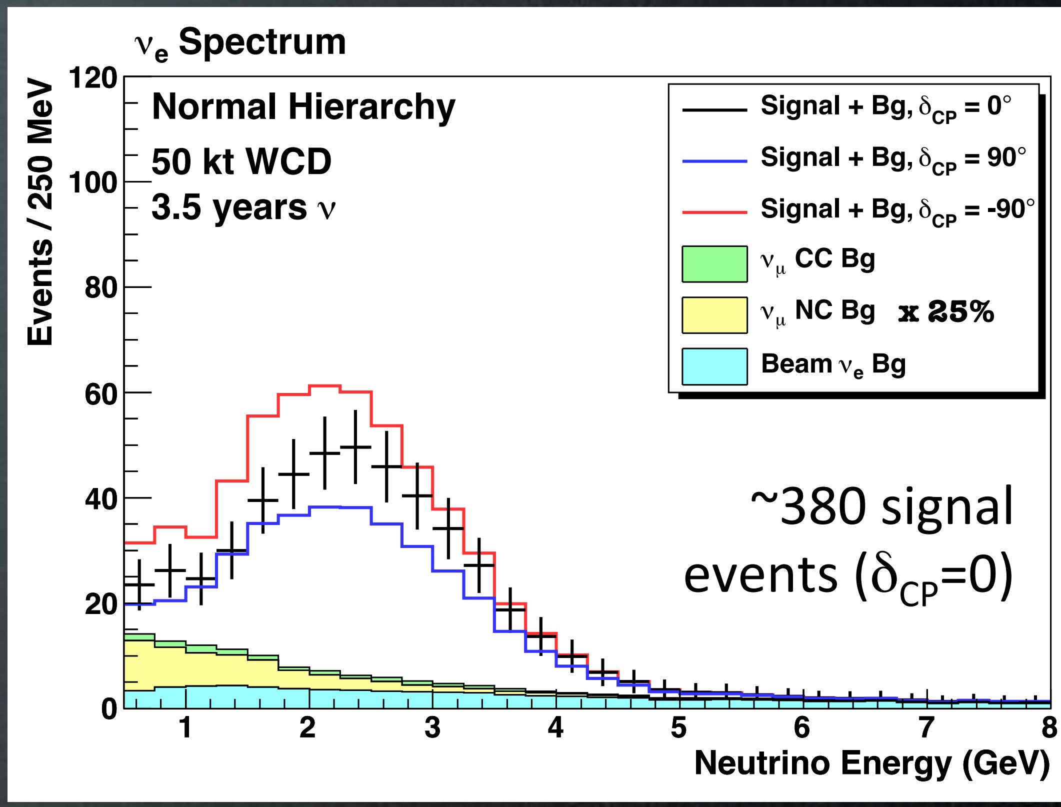
SK1 2 – 3 GeV



- Original LBNE optimization included a multidimensional cut to improve pi0 rejection

Final LBNE π^0 Rejection



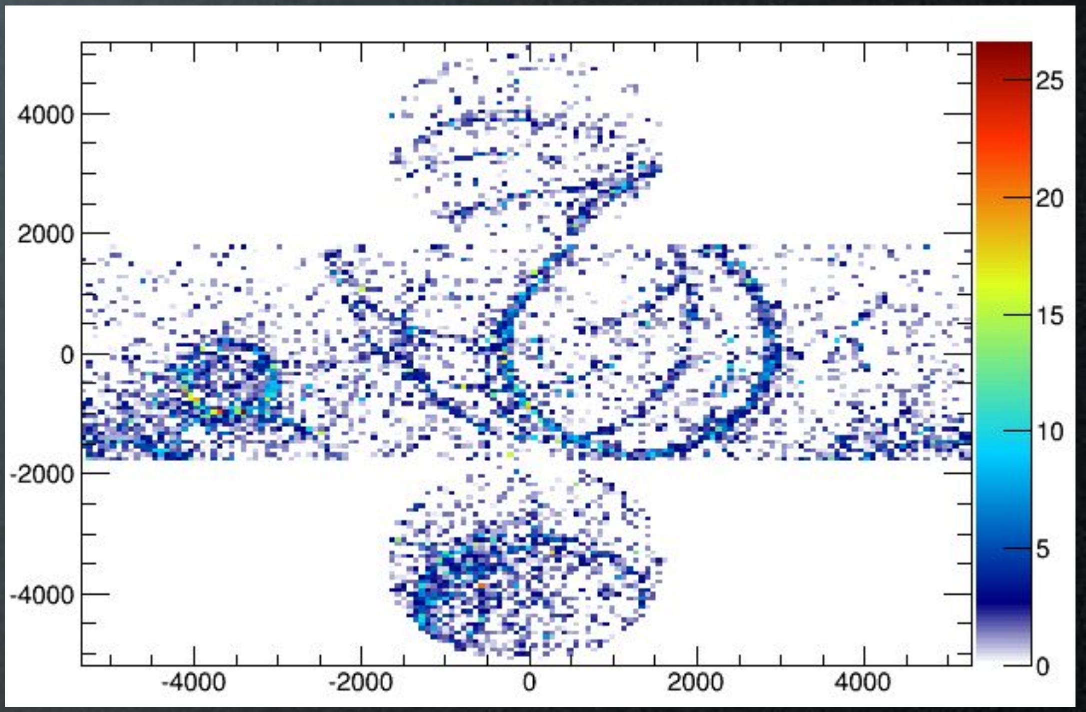


- π^0 rejection cut depends on reconstructed ν_e spectrum
    - Need to get the correct beam flux spectrum to properly predict π^0 rejection in reconstructed E_ν bins
- Work to do this with FiTQun has already started

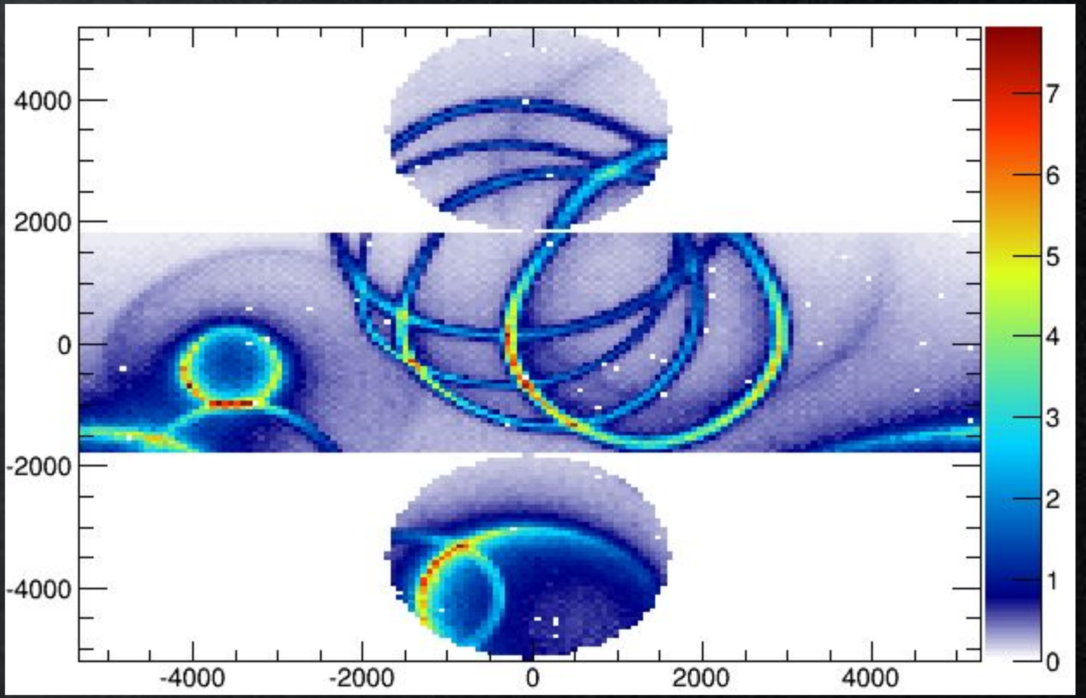
Multi-Ring Events

- Previous CCπ efficiency was between 20% - 35%
  - Large improvements are possible, since this mode is dominant at the DUNE 1st oscillation maximum
- Dedicated CCπ^+ fitters are under development in T2K
  - Event selection for CCπ^+ & CCπ^0 is already possible with existing multi-ring reconstruction

Hit Charge Distribution



Reconstructed Predicted Charge



Summary / Next Steps

- Next step is to modify sensitivity code to accept several different signal selections (CCQE, $CC\pi^{+}$, $CC\pi^{0}$, etc.)
  - Large gains may be possible at the 1st oscillation maximum
- FiTQun is now adaptable to a variety of different detector geometries and photosensors
- A large detector simulation using WCSim has been produced (via DUNE+GENIE event vectors produced by Elizabeth)
  - This can be used to produce a more realistic efficiencies in a larger detector size
- Improving THEIA's sensitivity to CP violation may be helpful in getting the first phase of the experiment built